

# Microelectromechanical Systems

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ARPA views Microelectromechanical Systems (MEMS) as a revolutionary enabling technology that merges computation and communication with sensing and actuation to change the way people and machines interact with the physical world. Using the same fabrication processes and materials that are used to make microelectronic devices, MEMS conveys the advantages of miniaturization multiple components, and integrated microelectronics to the design and construction of integrated electromechanical systems.

MEMS is a manufacturing technology that will impact widespread application including: miniature inertial measurement units for competent munitions and personal navigation, distributed unattended sensors for asset tracking and environmental/security surveillance, mass data storage devices, miniature analytical instruments, a range of embedded pressure sensors for passenger car, truck and aircraft tires, non-invasive biomedical sensors, fiber-optic components and networks, distributed aerodynamic control, and on-demand structural strength. The long-term goal of ARPA's MEMS program is to merge information processing with sensing and actuation to realize new systems and strategies for both perceiving and controlling systems, processes and the environment. Short-term goals include: demonstration of key devices, processes and prototype systems using MEMS technologies; development and insertion of MEMS products into commercial and defense systems; and lowering the barriers to access and commercialization by catalyzing an infrastructure to support shared, multi-user design, fabrication and testing.

The MEMS program has three major thrusts: advanced devices and processes, systems design and development, and infrastructure. These three thrusts cut across a number of projects and focus application areas including: inertial measurement, fluid sensing and control, electromagnetic and optical beam steering, mass data storage, signal processing, active structural control, precision assembly and distributed networks of sensors and actuators.

## Advanced Devices and Processes

Advanced devices and processes will exploit monolithic actuators, sensors and electronics to achieve new functionality, increased sensitivity, wider dynamic range, programmable characteristics, designed-in reliability and self-testing. New device concepts include: the integration of microdynamic devices with communication, control and computation components, miniature electromechanical signal processing elements (tuning elements, antennas, filters, mixers), miniature optomechanical devices (cross-bar switches, fiber-optic interconnects and aligners, deformable gratings and tunable interferometers), force/motion balanced accelerometers and pressure sensors, miniature analytical equipment (gas chromatography and mass spectrographs on a chip, DNA analysis chips), process control (HVAC equipment, mass flow controllers), and simultaneous, multi-parameter sensing with monolithic sensor clusters. The long-range goal of this thrust is to produce technology that allows the system designer to intermingle sensing, actuation, computation, communication and control. Examples of projects in this area include: MEMS surface micromachining processes integrated with all-CMOS microelectronics for low-cost, monolithic motion detection (safing, fusing and arming functions, tamper detection, automotive impact sensors), integrated actuators and optical waveguides for extreme and hazardous environment sensing, polymerase

chain reaction chambers with integrated heaters, thermistors, fluid valves, and channels (field-portable pathogen detection, enhanced and accelerated sequencing) and fluid valves and regulators appropriate for hydraulic and pneumatic systems pressures and flows. Advances in these areas will be paced by, among others, the development of new material deposition, removal and shaping processes, the merger of hybrid processes (e.g. microelectronics and optoelectronics), and control strategies for inertia-negligible, friction/viscous force-dominated structures.

## Systems Design and Development

Systems design and development will focus on high-density arrays that achieve their function or macroscopic action through the coordinated microscopic action of multiple, identical, and relatively simple microactuators. The batch fabrication inherent in photolithographic-based processing, makes it possible to fabricate thousands or millions of components, and their interconnections, as easily and at the same time that it takes to fabricate one component. This multiplicity allows additional flexibility in the design of electromechanical systems to solve problems. Rather than designing components, the emphasis can shift to designing the pattern and form of interconnections between thousands or millions of components. The diversity and complexity of function in ICs is a direct result of the diversity and complexity of the interconnections and it is the differences in these patterns that differentiate a microprocessor from a memory chip. MEMS makes available a disturbed approach to design for solving problems in electromechanical systems design.

Requirements for the construction of high-density array MEMS include the development of a high-yield, high-uniformity fabrication processes for constituent components and algorithms for embedded control of multiple ( $> 100,000$ ) devices to achieve macroscopic function through distributed, coordinated action of individual elements. New concepts in the integration of multiple devices to form microdynamic systems include: distributed, plug-in sensors interconnected by wired or wireless networks sharing a common communication/power bus, high-fidelity inertial sensing from massively-parallel inertial elements integrated with signal processing circuitry, combustion control through distributed and precise control of reactants and conditions, small-area and low-power displays based on electromechanical deferrable gratings, and increased structural strength from distributed detection and adjustment of material buckling. High-density microactuator arrays ( $>100/\text{cm}^2$ ) would find applications in deformable surfaces for underwater or air vehicle control, high-density data storage systems, integrated source/optics projection displays, direct-wire fine-line lithography, distributed and accelerated analytic instrumentation, precision parts handling and assembly, and on-demand structural strength.

## Infrastructure

Infrastructure activities are focused on the services, tools, processes and equipment that will accelerate the affordability and manufacturability of MEMS devices and systems. While MEMS is a new way to make electromechanical systems that leverages microelectronics fabrication, significant differences in MEMS devices and fabrication processes, particularly at end-stage processes and interfaces, require new processing and packaging approaches. Conventional electronics packaging and interconnects seek to provide an appropriate electrical, thermal and mechanical environment for networks of electronic devices. Such packaging often also aims to shrink large quantities of electronics into a small volume, with attendant improvements in performance and reliability. The interface/package manufacturing part of this thrust acknowledges that in many cases the electronics and interconnections need to be not only small, but conform to, rather than dictate the system form factor. Examples are the skin of a hypervelocity missile, an unattended sensor, or the knee joint of an exoskeleton. In addition to

providing appropriate isolation or protection from some of the environment, packages for MEMS components and systems need to also allow controlled access to selected physical parameters that are either being sensed or controlled. Examples include deformable gratings that need access to light but need to operate in vacuum, integrated fluid systems (access to samples for analytical instruments, distributed miniature flaps that need to be in the boundary layer of an aerodynamic stream), and silicon carbide sensors that need to access pressure and temperature inside combustion engines.

Design and simulation tools that combine process descriptors; material characteristic data bases; finite-element packages for structural, electromagnetic fields, fluid interactions, electrostatic fields and electronic device modeling are an integral and continuing part of the infrastructure. Also being supported under this thrust area are CAD design and layout tools that incorporate and allow free-form geometries, cell-design libraries (submission protocols, archiving and recall), parameterized cell models, and dynamic visualization simulators. A rich and robust design and simulation environment is necessary to provide an infrastructure for current and future activity in the field.

Complementing and synchronized with the design and simulation tools developments are the support and development of affordable, distributed fabrication services or users in industry, academia and the government. A surface micromachining fabrication service has and is providing hundreds of distributed users from diverse backgrounds affordable access to micromachining processes at regular, scheduled intervals. This access is accelerating both innovation and commercialization of MEMS products and is being used by other Federal and service agencies for education and training programs in MEMS.

#### Defense and Technology Impact

MEMS components and systems are moving from being scientific curiosities to applications in sensors, displays and data-storage. DoD has been slow to embrace these technologies because of a lack of demonstrated manufacturability, designability and relevant systems concepts. This program has visibly reduced the risk associate with MEMS devices by developing key technologies and merging advances in MEMS with wireless communication and low-power electronics to demonstrate that DoD-relevant devices can be designed and manufactured. Examples include: high dynamic-range accelerometers for precision munitions; portable inertial guidance systems for personal navigation and head-mounted display orientation sensing; on-demand structural strength for lighter weight platforms; passive IFF systems, condition-based maintenance with embedded MEMS devices; hazardous environment (vehicle engines) sensors, multi-parameter unattended ground sensors for wide-area surveillance, and flow-control deformable surfaces for advanced maneuverability of air/undersea vehicles and projectiles.

Because devices and systems that will be produced or enabled by this program can be expected to be deployed in large numbers, affordability and manufacturing issues are key to DoD use. The manufacturing processes resulting from this program would be capable of producing a diversity of components and systems without retooling and to realize near-equivalent unit costs form either prototype or full-scale production quantities. Procurement costs for new components, systems and spare parts would decrease, inventory/storage costs would be reduced and manufacturing capability/facilities could be consolidated. With many of the proposed technologies' starting points based on proven, mature integrated circuit fabrication techniques, the development, acceptance and sourcing of the devices and technologies will be accelerated.

The ability of MEMS to gather and process information, decide on a course of action and control the environment through actuators increases the affordability, functionality and the

number of smart systems. Microdynamic devices and systems will be merged with communication, control and processing components; three-dimensional microfilming/machining technologies; and embedded/flexible packaging techniques. The range of current design and simulation tools for electronic devices will be extended with three-dimensional mechanical and electric field modeling modules and process-related material property modules to improve the design, integration and operation of microdynamic devices, integrated wireless communication components and low-power electronic systems. The enhanced capability enabled by MEMS will increasingly be the product differentiator of the 21st century, pacing the level of both defense and commercial competitiveness.